

Bose-Einstein Condensation of Very Cold Atoms

Randall G. Hulet





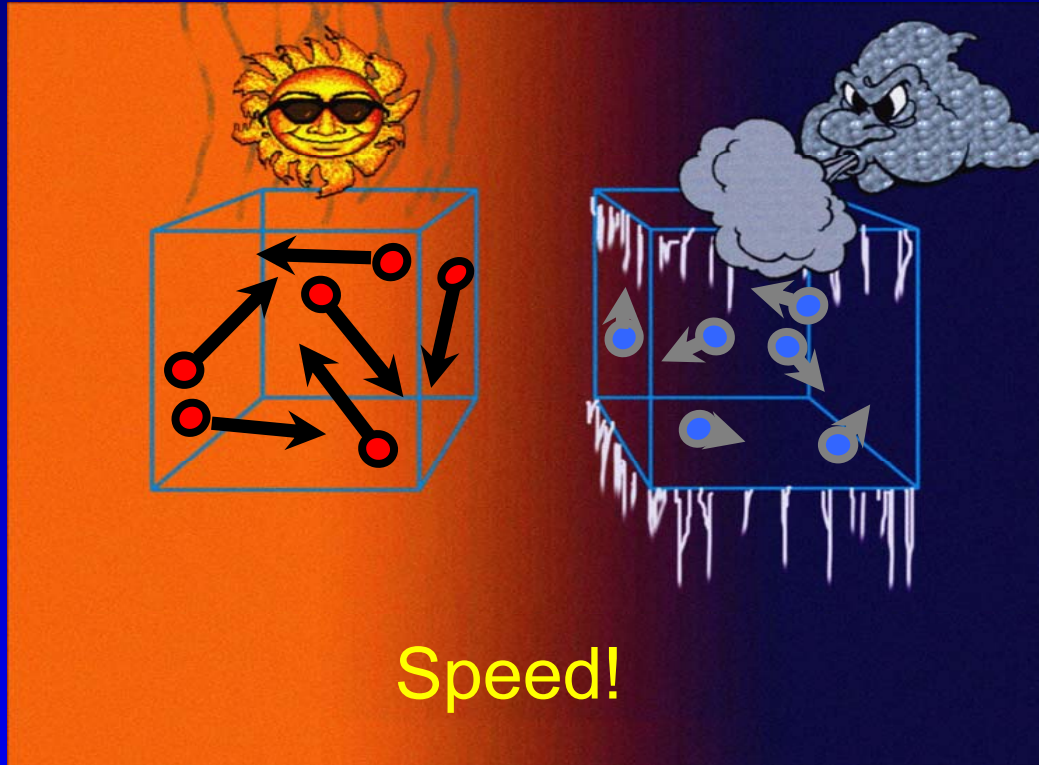
Oppenheimer

Houston

Millikan

Einstein

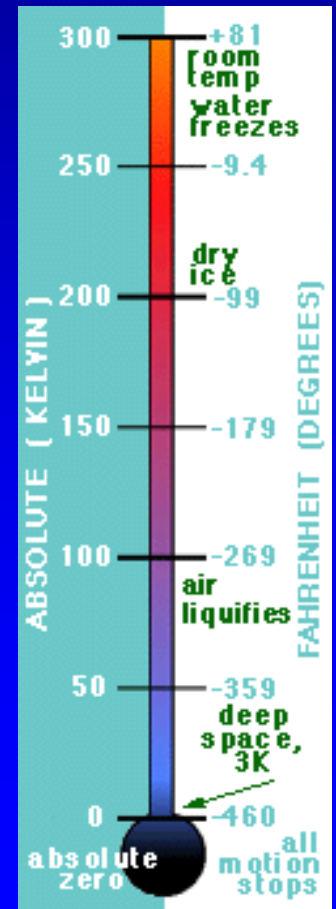
What is Temperature?



$T \propto v^2$ so slower \Leftrightarrow colder

Kelvin (absolute) temperature scale:

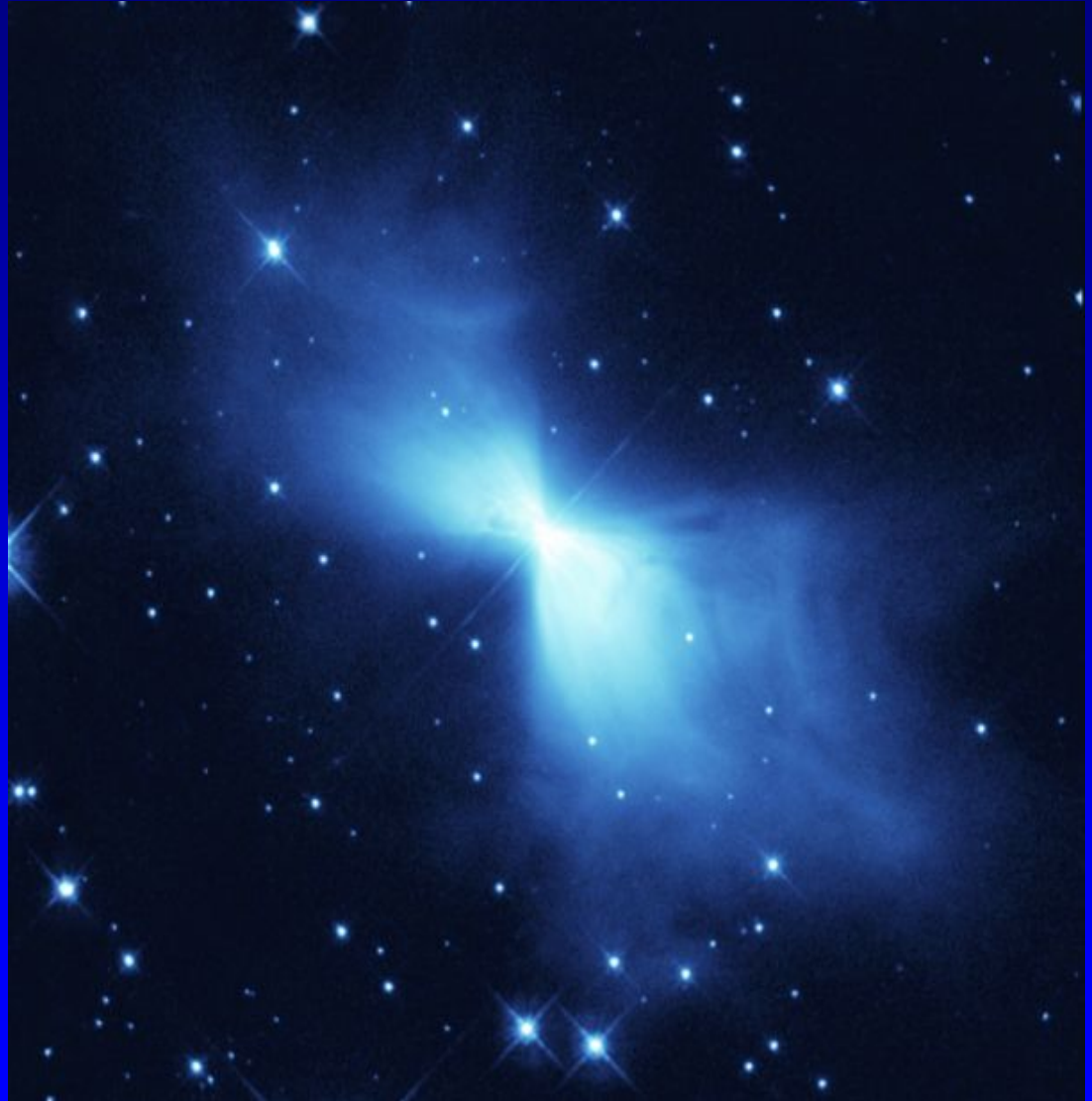
$$T(\text{Kelvin}) = T(\text{Celsius}) + 273^\circ$$



Boomerang Nebula

The (Naturally) Coldest Region of the Universe

Adiabatically cooled to ~ 1 K
by 1500 years of expansion



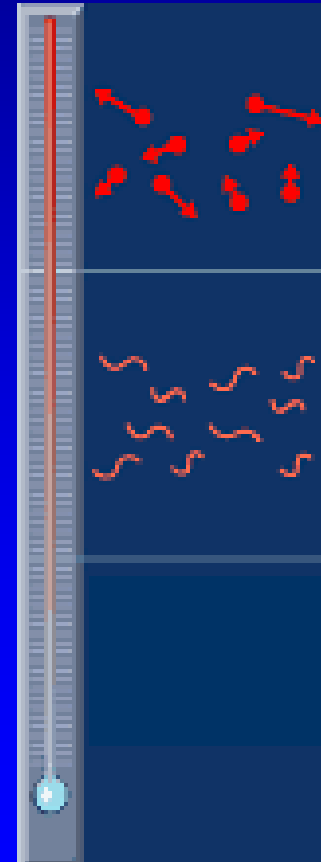
R. Sahai and L.-A. Nyman, *Astro. J.* **487**, L155 (1997)

The Quantum Mechanics of Cold

- Wave/particle duality
 - wavelength $\propto 1/(\text{mass} \times \text{velocity})$

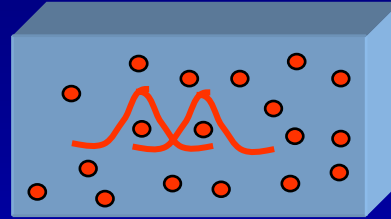
High temperatures – particle-like

Low temperature – wave-like



The "Quantum Regime"

- Quantum regime:



$$\text{Wavelength} \propto 1/(\text{mass} \times \text{velocity})$$

- Easy for small mass, i.e. electrons (e diffraction, etc.)
- Not so easy for atoms: $T \approx 100$ nano-Kelvin
- Amazing new phenomena appear in the quantum regime

What Happens in the Quantum Regime?

Depends! There are two kinds of particles:

Fermi-Dirac or “fermions”

Electrons, protons, neutrons

composites with *odd* number
of e, p, and n:

Lithium (${}^6\text{Li}$)

Bose-Einstein or “bosons”

composites with *even*
number of e, p, and n:

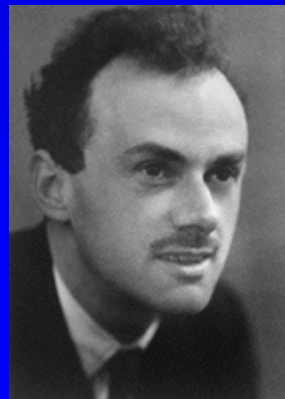
Hydrogen (H)

Helium (${}^4\text{He}$)

Lithium (${}^7\text{Li}$)



E. Fermi

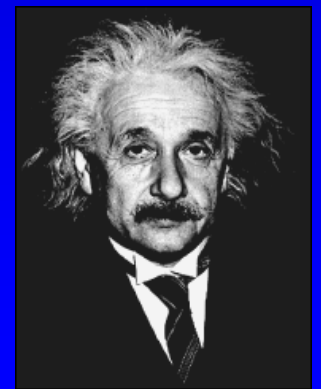


P.A.M. Dirac

1924-26



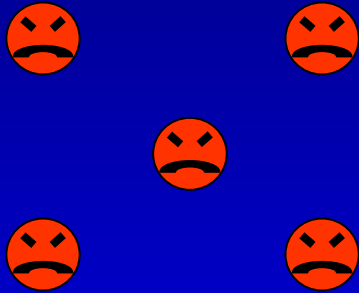
S.N. Bose



A. Einstein

Bosons vs. Fermions

Fermions cannot occupy same space:



Bosons can!

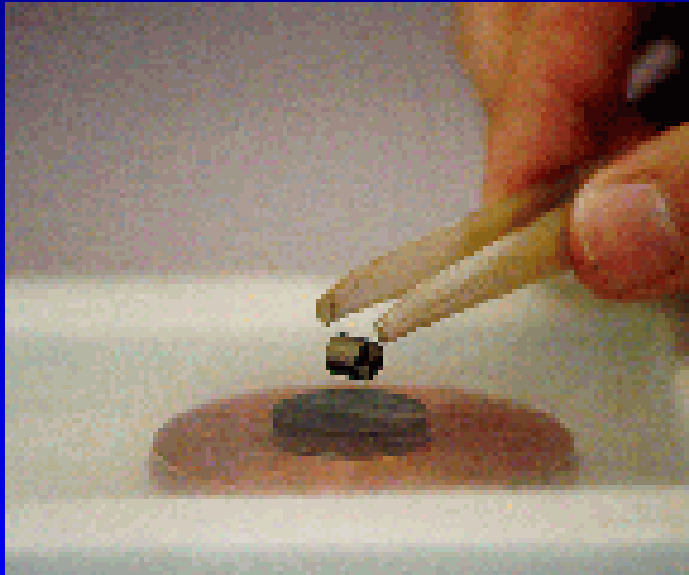


- Periodic table of the elements
- Stabilizing cold stars

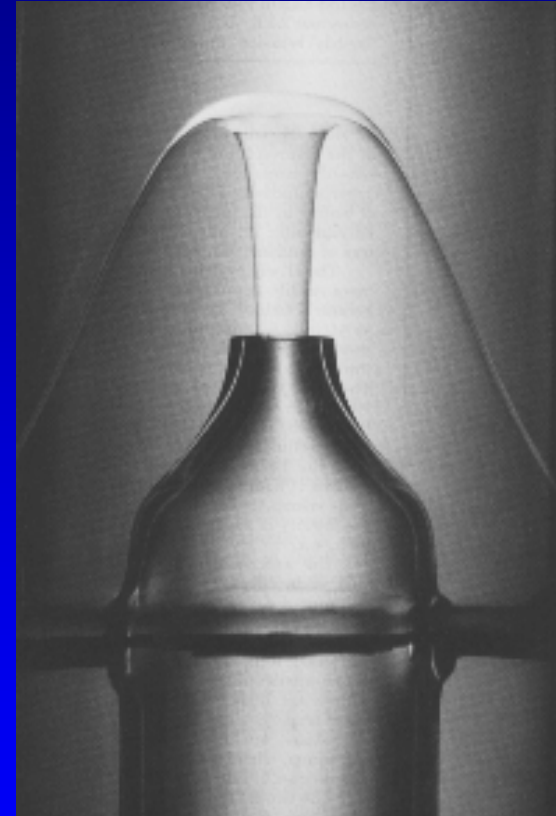
- Bose-Einstein condensation (BEC)

A BEC is a *phase transition* to a collective quantum state

Examples of Phase Transitions Involving Bosons and Fermions



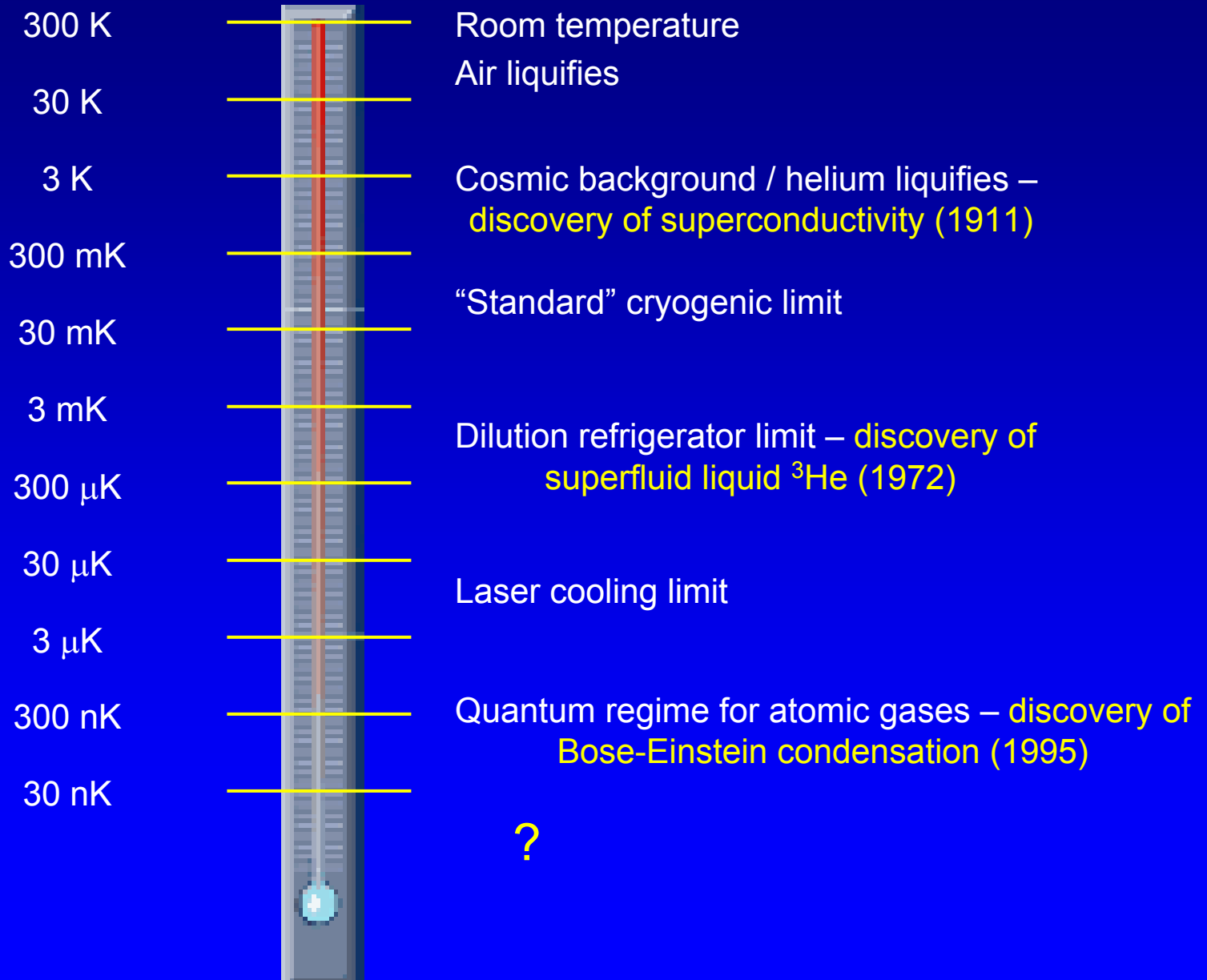
Superconductor



Superfluid

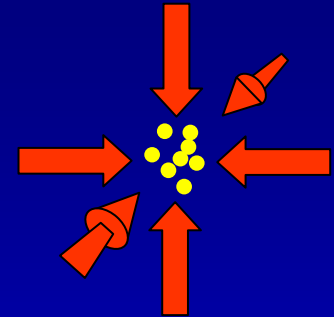
A primary motivation is to understand high-T superconductors

Decade Thermometer

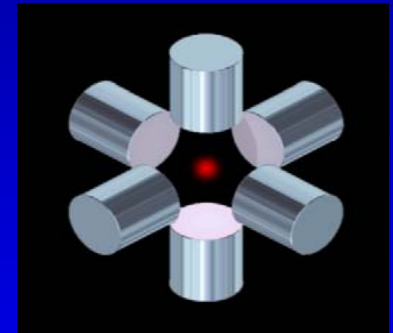


Methods

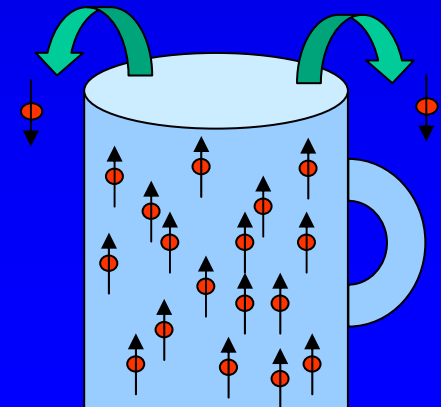
- Laser cooling
micro-Kelvin



- Atom trapping

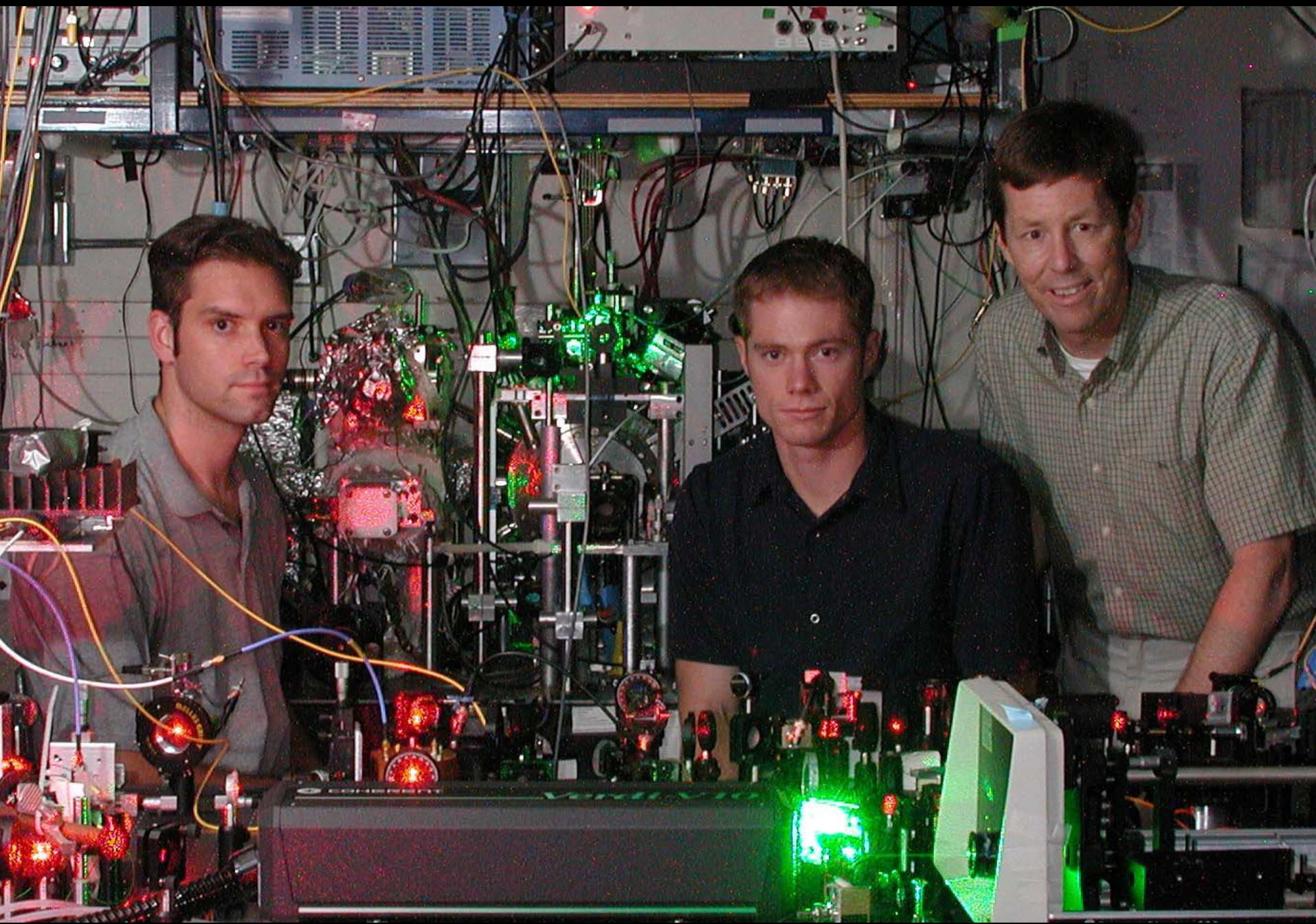


- Evaporative cooling
micro-Kelvin \rightarrow nano-Kelvin



Evaporative Cooling



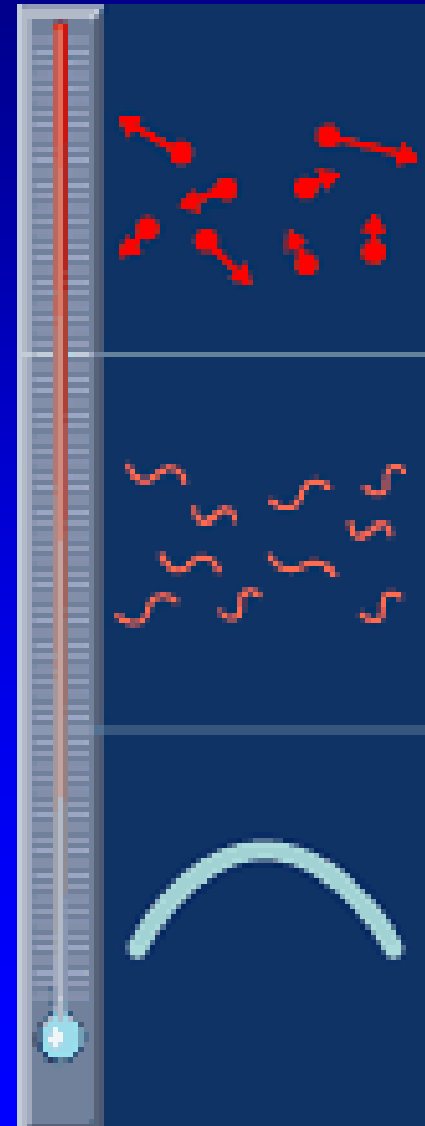


Bose-Einstein Condensation (BEC)

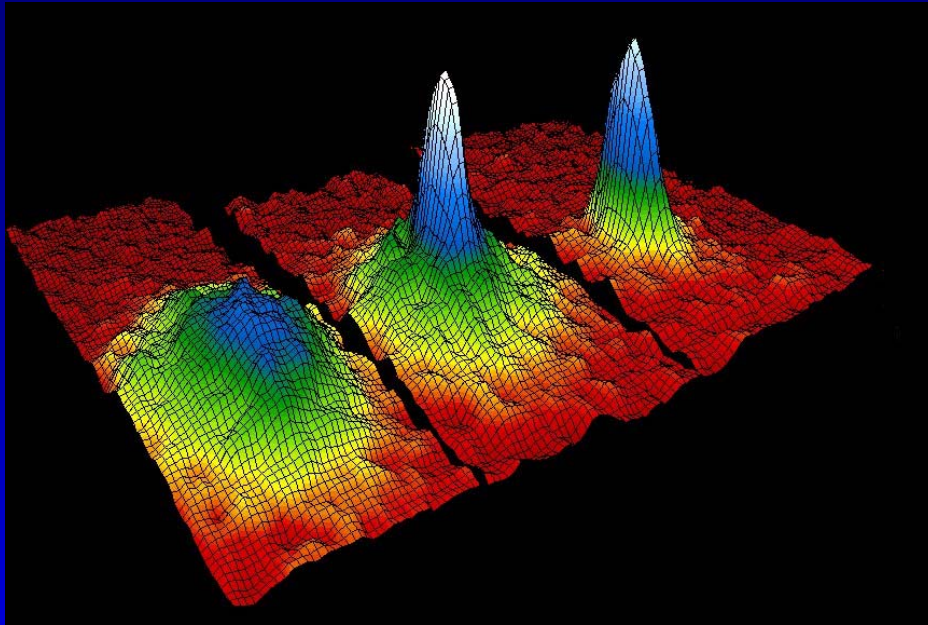
High temperatures – particle-like

Low temperature – wave-like

Very low temperature - waves overlap and **bosons** undergo a phase transition to a BEC



BEC of a Trapped Gas



U Colorado, 1995

So What Is It?

BEC \leftrightarrow ordinary gas

Pure musical tone \leftrightarrow noise

Laser light \leftrightarrow flashlight

Texas A&M Aggie Band \leftrightarrow Rice Marching Owl Band



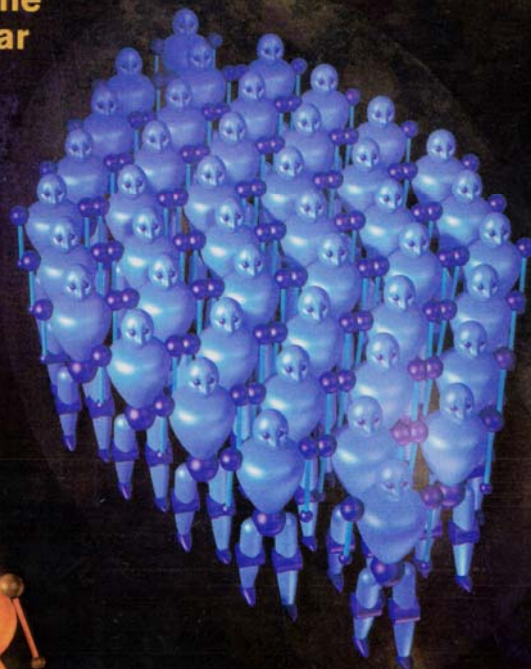
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ASSOCIATION FOR THE
ADVANCEMENT OF
SCIENCE

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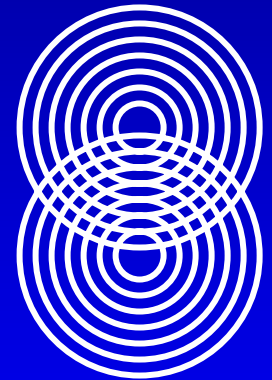
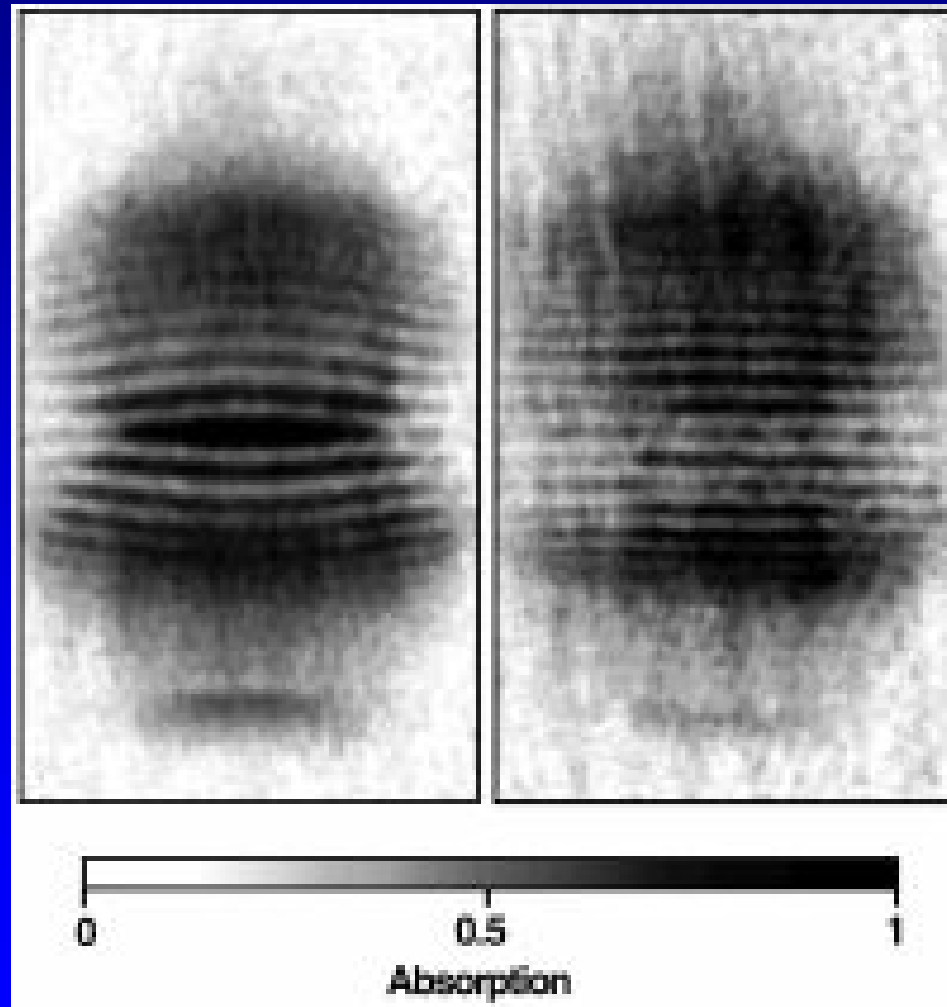
**Molecule
of the
Year**



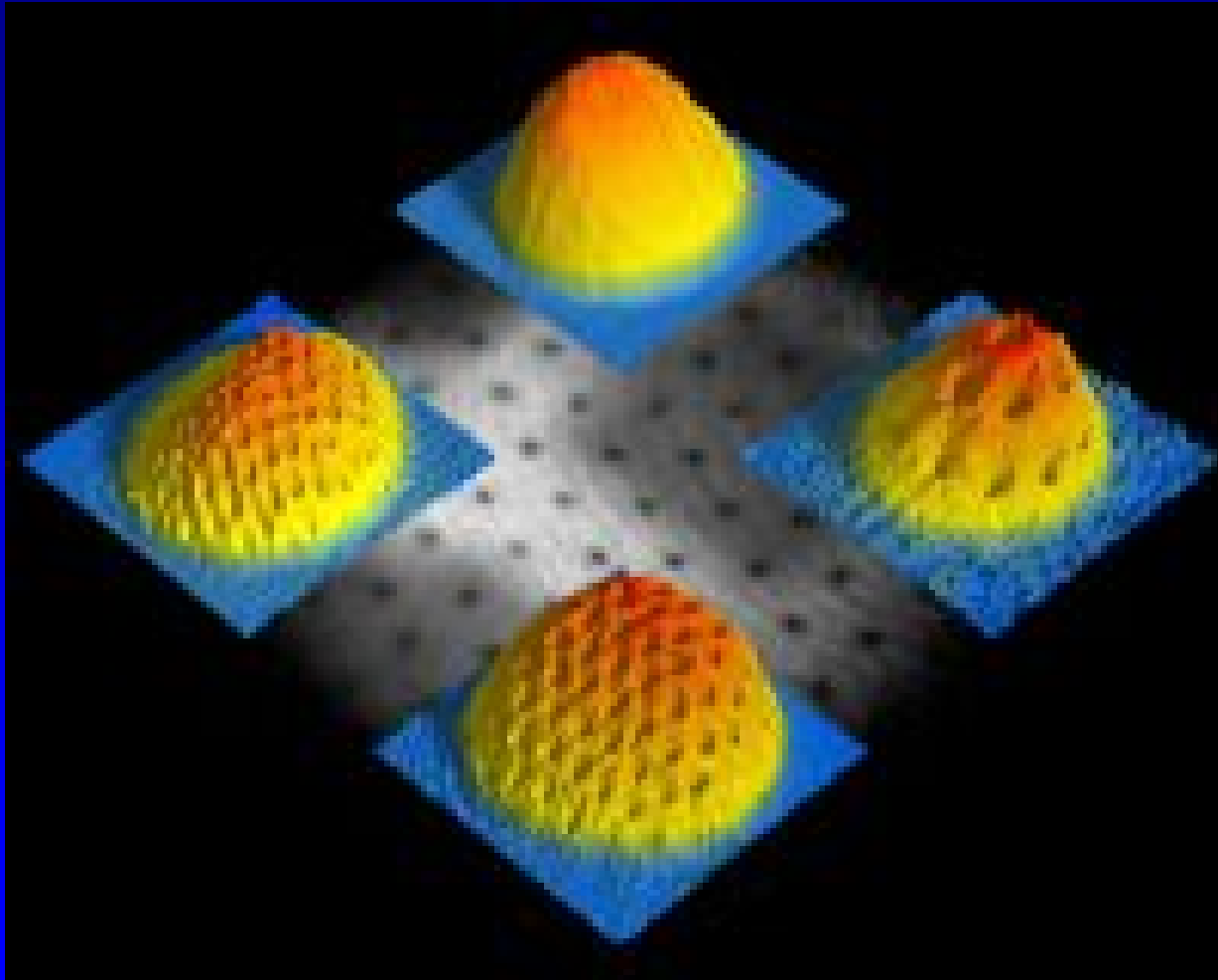
*the
Bose-Einstein
Condensate*



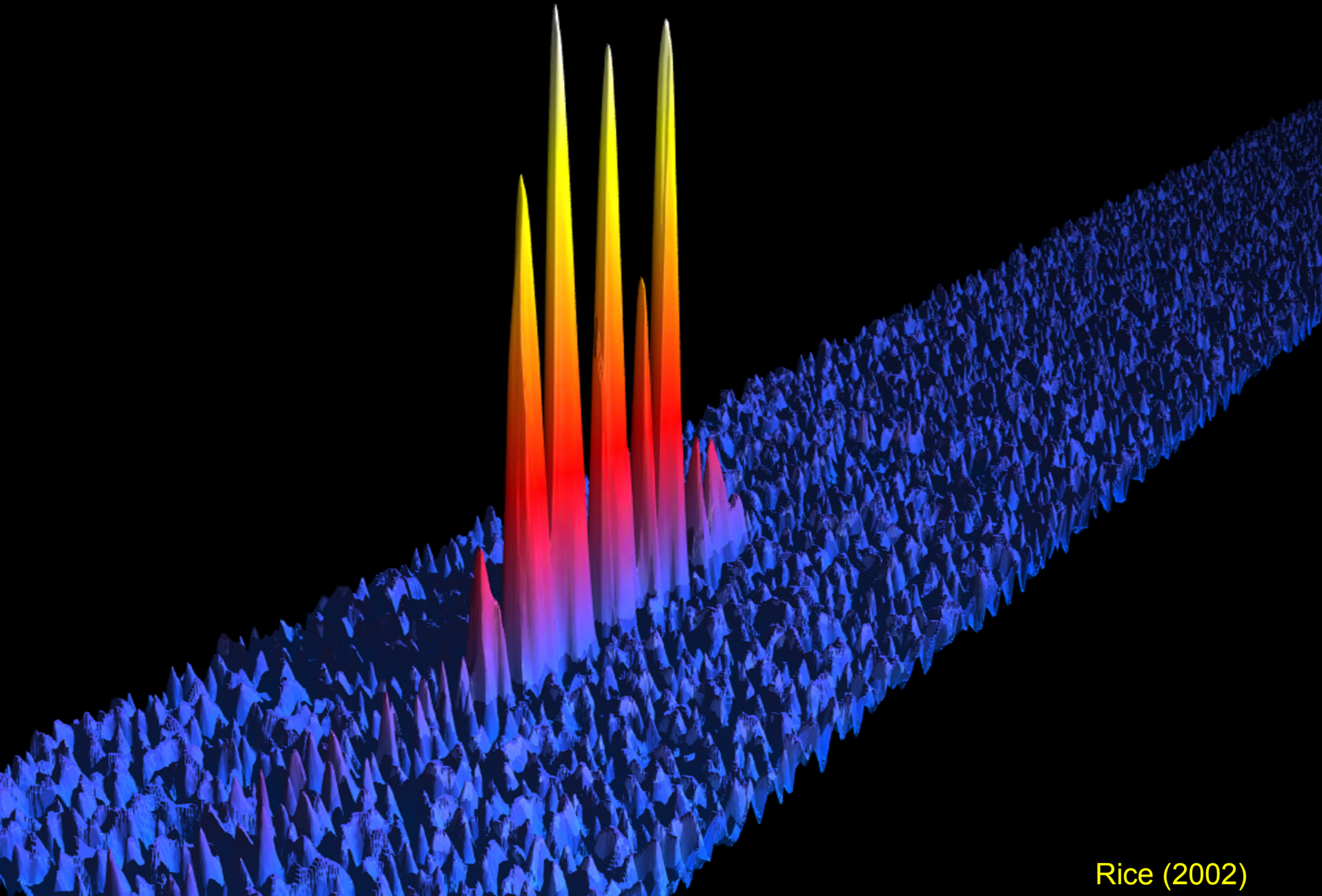
BEC's Interfere Like Waves!



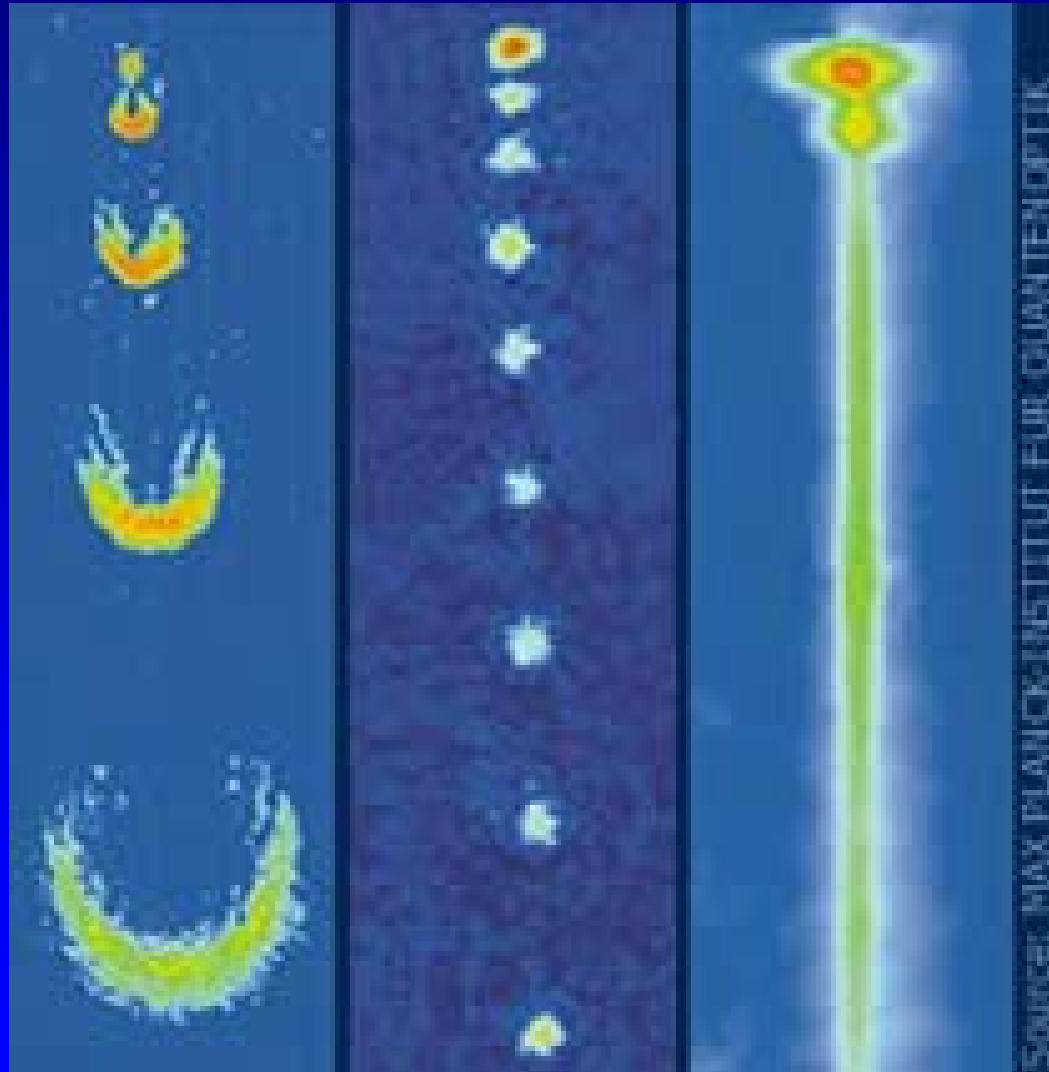
Vortices in the Superfluid



Atomic Solitons



Atom Lasers



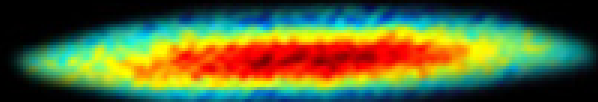
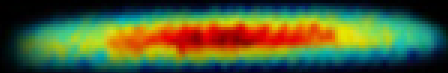
Fermi Pressure

Bosons

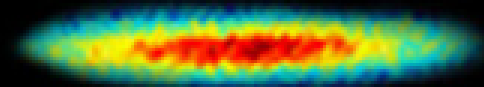
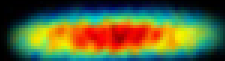
Fermions



810 nK



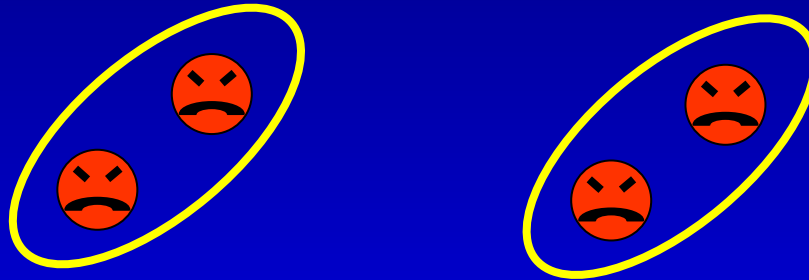
510 nK



240 nK

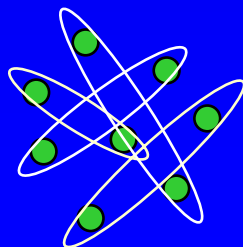
Fermion Pairing

- Fermions cannot directly form a BEC
- However, pairs of fermions are bosons!



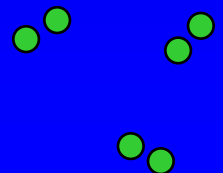
- Condensation of fermion pairs gives
 - Superconductivity
 - Superfluidity ^3He
 - Dilute gas: Interactions variable

Weakly interacting:



?

Strongly interacting:
BEC of molecules



Applications and Motivation I

Basic Physics:

- Experimental realizations of the paradigms of condensed matter physics:
 - Models of high- T_c superconductivity
 - Pseudo-gap
 - Luttinger liquid, spin-charge separation, quantum Hall effect ...

Quantum gases are pure, defect-free, experimentally well-controlled systems, in which many of the parameters (density, number, temperature, interaction strength, lattice periodicity and strength, ...) are readily varied.

Applications and Motivation II

- No direct applications yet
- Promising directions:
 - atom laser
 - direct-write atom lithography
 - atom interferometry (inertial sensors)
 - gravity gradiometers
 - rotation sensors (ring gyro)
 - atomic clocks

